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CATASTROPHE RESILIENCE RELATED TO URBAN NETWORK SHAPE: PRELIMINARY ANALYSIS.

Anna Bozza[1*]**, Domenico Asprone**[1]**, Alessandro Fiasconaro**[2]**, Vito Latora**[2]**, Gaetano Manfredi**[1]

[1]Department of Structures for Engineering and Architecture
University of Naples Federico II
Via Claudio 21, 80125 Naples - ITALY
{anna.bozza, d.asprone, g.manfredi}@unina.it

[2]Department of Applied Mathematics
Queen Mary University of London
Mile end road, London E1 4NS - UK
{a.fiasconaro, v.latora}@qmul.ac.uk

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Abstract. *People living in a city represent the most important agents of the urban system. In fact, people organize bits of the city, while organizing their own lives, hence directly influencing much of the city structure, from both a human point of view and a topological one. Such a self-organizing process reflects on both safety and life quality of citizens and efficiency of city services.*

As a result, in order to better manage a city one should know its inhabitants' behaviour and its topological configuration too. An ambitious goal that can be pursued in the sense of complex networks theory approach, studying the urban centre as a hybrid social-physical network made by both human and physical components (HSPN)[1].

In this study different topological structures and geometric shapes of cities are investigated, focusing on the efficiency of cities themselves, and their resilience. Moreover, due to the current increasing risk of natural and human-induced disaster threatening local communities, urban societies are suffering a gradual reduction of their actual and potential resilience, as their ability to cope and withstand with external events.

To this purpose, seismic events are simulated for each investigated urban geometry, referring to the most common shapes existing worldwide. A novel systemic measure of the expected damage state is here defined, which allows for a vectorial measure of the city efficiency in its entirety. Urban resilience is assessed as an integral measure, before, during and after an extreme event occurs. Thence, a recovery strategy is hypothesized and the efficiency of the HSPN network and the resilience of the city are then evaluated and compared in a time-discrete analysis.

1 INTRODUCTION

Urban environment can be easily studied as a complex system, made by several different components and agents coexisting and mutually interacting. The main constituents of such a structure are the social ones, that are the citizens. They are semi-autonomous agents, which take choices and act following rules, such as laws, codes, guidelines, but also trends and traditions. These are rather like the “DNA” of the city, affecting its shape both from a human point of view and a topological one [2]. In fact, such social dynamic, together with urban planning choices performed by local governments, produces different outcomes, depending on the geographical configuration of the single urban system and on its sociological, cultural and economic background.

Hence, the resulting urban structure shows wide differences from city to city, which can influence the overall behaviour of local centres both in terms of the quality of life and safety of citizens. In order to understand how much and in which way this happens, one need to characterize the topological configuration of the city itself, once the features of both its physical and human components are well known.

To face such an issue, the modeling of the city as a hybrid social-physical network (HSPNs) [1] can be performed. HSPNs' approach is an innovative mean which can lead to the effective enhancement of the city resilience and efficiency, according to a human-centric perspective. Moreover it also allows for the improvement of urban planning instruments and risk management.

HSPNs’ modeling allows to focus on connectivity too, in the sense of complex networks theory approach. In fact, it has been studied as a fundamental feature of some human behaviours, depending on “if” and “how” they are linked together to form a city [3].

Several efforts have also been made during last years for enhancing urban planning instruments and control urban evolving dynamics. Actually, one should let a city evolving itself while contextually performing strategic and catalytic interventions, such as in the case of the modern “top-down” approaches, so as to catalyse modern self-organization growth processes around specific areas [4]. The “physiological” behaviour of a city would be thence respected, and actions would be undertaken just acting on the enhancement of the efficiency of city patterns according to citizens’ choices and preferences.

The focus of this study is just to investigate different topological structures and geometric shapes of cities, which can already exist and also result from modern urbanization processes. Nowadays modern communities are seriously threaten by global risks, such as climate change, natural catastrophes and human-induced disasters. Moreover they are ever more exposed and vulnerable to such risks, given the high urbanization and the high concentration of economic and strategic activities in urban centres. Modern urban systems are suffering a gradual reduction of their actual and potential resilience, as their capability to face and to bounce back from external events.

A particular focus is done on seismic risk, through the simulation of earthquakes with different values of peak ground acceleration (PGA) for each investigated urban geometry. Thence, a recovery strategy is hypothesized, accounting for cheaper damaged buildings to be repaired and the efficiency of the HSPN network and the resilience of the city are then evaluated in a time-discrete manner.

New paradigms are recognised in the field of damage assessment allowing for a systemic measure of damages to be performed. Efficiency evaluated in the sense of complex networks theory is merged together with engineering damage assessment of buildings and streets, according to the performance based earthquake engineering methodology. As a result an integral measure of the impacts of seismic events on urban centres is assessed.

Urban resilience and city efficiency are evaluated, before, during and after the seismic event occurs according to different typical geometric shapes of the street patterns and building locations. In fact, cities are modeled with different geometric shapes referring to the most common existing worldwide, all having a grid-like layout, which is particular to cities whose shapes are the result of large-scale top-down planning efforts, which represent one of the preferential option for modern urban city planning [7].

The different city shapes which are herein investigated have already been classified within different scientific studies. In particular, circular, rectangular, hexagonal and star shapes are modeled.

Moreover, according to the complex networks approach, it is also accounted for particular aspects concerning the number of nodes (representing citizens, strategic buildings, commercial activities and/or residential buildings), the number of links (streets) and their geographic site. These are variables which deeply influence cities' behaviour, being urban areas modelled as graphs.

Cities' behavior, as they are modelled as graphs, apart from the overall geometry of the network itself, is described by the number of nodes (representing citizens, strategic buildings, commercial activities and/or residential buildings), the number of links (streets) and the geographic site of them. Given that, the research project will be based on three main aspects, accounting for all these variable aspects, within two main subprojects:

1. urban resilience and network efficiency assessment for different urban geometries, having the same number of buildings but different locations together with different number of links, when earthquakes with different magnitude occur;
2. urban resilience and network efficiency assessment for different urban geometries, hence different number of links, being the same for each geometry both the number and location of buildings, when earthquakes with different magnitude occur.

2 CITY MODELING ACCORDING TO THE COMPLEX NETWORKS THEORY

2.1 HSPNs modeling

A system of typical street patterns is constructed for the modeling of each urban geometry, into a GIS environment, which is inspired to the European and US major cities and ancient city centres.

Then the primal graph is constructed whereas a set of nodes represent street junctions and another one represents residential buildings.

In order to model the cities, for each studied configuration some assumptions and hypothesis are made to characterize it. Structural typology is assumed to be frame buildings made of reinforced concrete, with all buildings designed for gravity loads. Referring to the Italian built environment, in fact, and to the building constructing practices in most of the European cities, it is known that reinforced concrete buildings usually exhibits plane parallel frame schemes and regularity both in plane and in height. This is for both, non-seismic designed and seismic designed buildings. Buildings considered for city scenario simulations are assumed to be typical 70s – 80s constructions, with number of storey being comprised between 2 and 5.

Citizens living in each city are accounted depending on the total floor area of each structural typology and assuming about 1 citizen each 30 square meters, as suggested by the database of the Italian Institute of Statistics, ISTAT. 1 dwelling each floor is assumed for 2-storey buildings, hence 100 – 150 sqm of total floor area each storey, 2 dwelling are assumed for 3-storey buildings (180 – 250 sqm), 4 dwelling are assumed for 4-storey buildings (300 – 450 sqm) and 6 dwelling are assumed for 5-storey buildings (500 – 600 sqm).

Moreover, the percentage of buildings with reference to their number of storey is taken fixed, given that the number of inhabitants is calculated depending on the total residential square meters for each simulated urban centre. Residential buildings are modelled for 10% as 2-storey, 40% 3-storey, 30% 4-storey and 20% 5-storey. This allow to compare more accurately and realistically data from scenario simulations, keeping in this way the number of citizens always in the same magnitude.

Also street network configuration is hypothesized assuming denser streets concentrations near the centre, being topologically different for each simulated city, according to its shape.

Different HSPNs are constructed, being divided into two typology, according to the research project:

- for each geometry, being fixed the street patterns and the number of designed buildings, four different configurations of residential HSPNs are designed, where the buildings location is always different (Figure 1 – 4);
- for each geometry, being fixed the number and the location of residential buildings, one different configuration of residential HSPNs is designed (Figure 5a – 5d).

HSPNs are then described by means of a graph with N = | Ɲ | nodes and K = | Ʊ| edges. Being Ɲ = {$ɳ_1$, $ɳ_2$, …, $ɳ_N$} and Ʊ = {$ʋ_1$, $ʋ_2$, …, $ʋ_N$}. Actually the modelled HSPNs consist of two set of nodes and two set of edges, being:

- $Ɲ_i$, the set of node intersections representing crossings in the street network;
- $Ɲ_b$, the set of building nodes;
- $Ʊ_{ss}$, the set of street segments, representing links between couple of node intersections;
- $Ʊ_{sb}$, the set of street segments linking street segments to building nodes.

The city graph can then be defined and is denoted by $G(Ɲ_i \cup Ɲ_b \cup Ʊ_{ss} \cup Ʊ_{sb})$. Different geometries are modelled , being inspired by the major European cities, as shown following:

- Circular (ex. Rome, l'Enfants' plan for Washington DC, Regent's park in London, Karlsruhe)
- Rectangular (ex. Savannah, Regensburg on the southern bank of river Danube, from Roman times [6]), better known as the typical structure of US modern cities, ex. Orlando, New York, Philadelphia, etc., they typically exhibits T-shaped crossing as self-organised urban networks. Also Venice and Cairo shows similar geometric shapes, actually they are not just rectangular but self-organised cities as well;
- Hexagonal/Octagonal (Vitruvius model) [5] [6]
- Star, ideal city model of renaissance, an example is the Italian city of Palma Nuova, outside Venice, originally accredited to the architect Scamozzi.

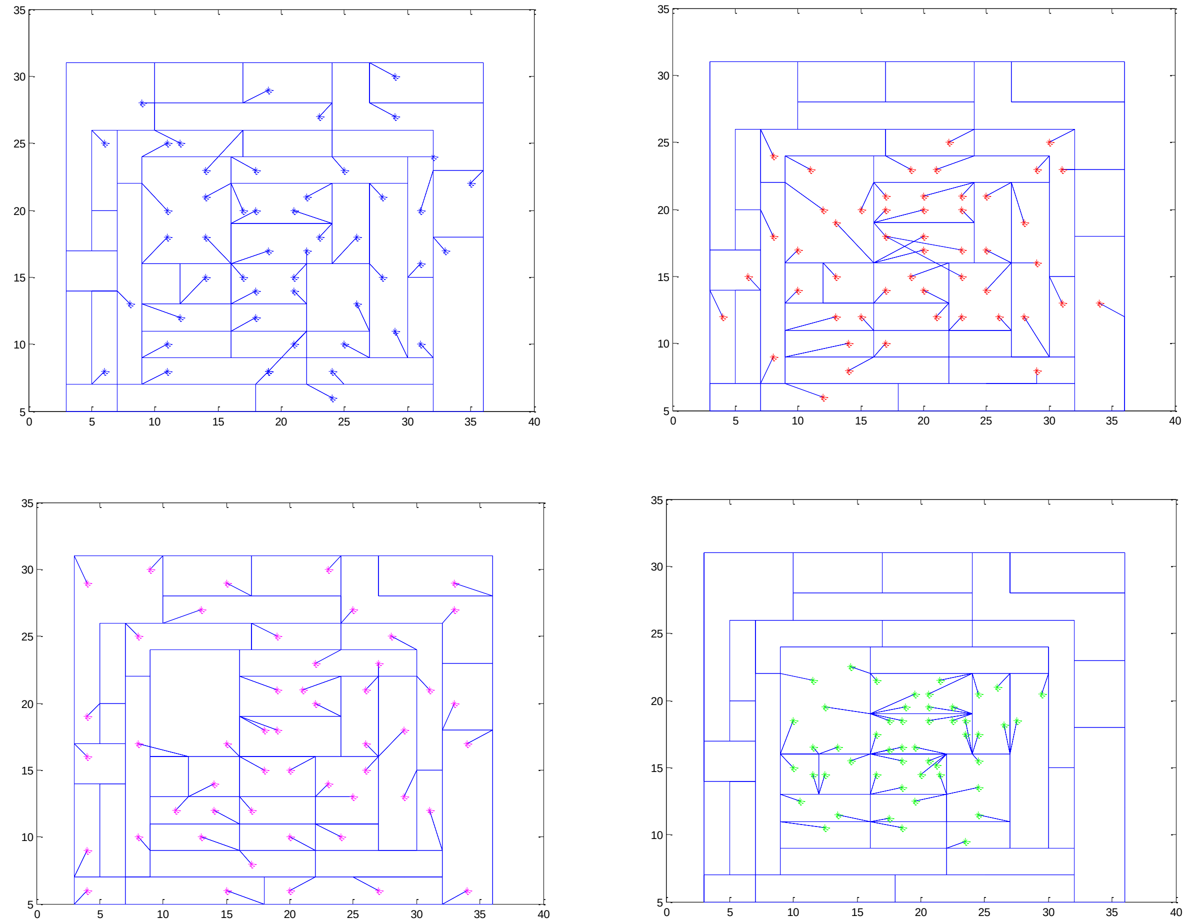


Figure 1 – Four different buildings spatially configuration for rectangular city shape

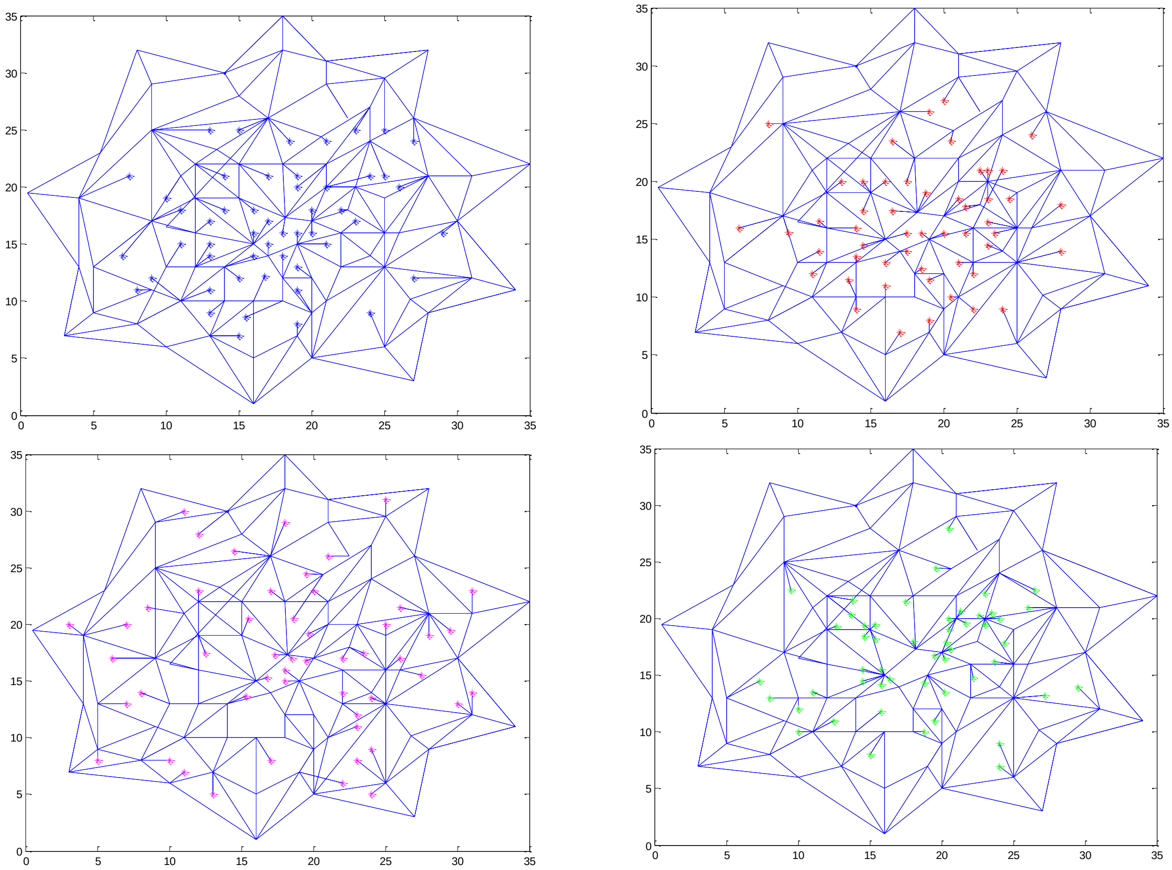
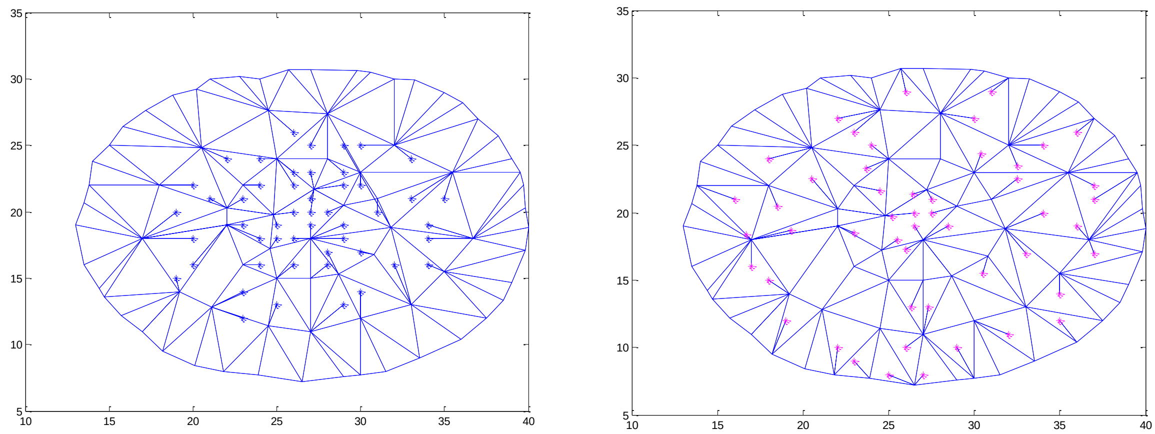


Figure 2 - Four different buildings spatially configuration for star city shape



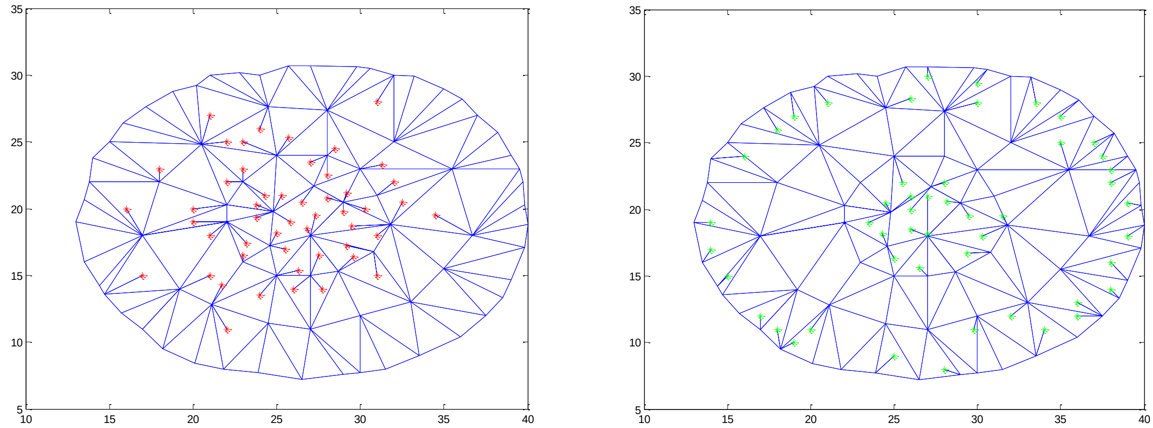


Figure 3 - Four different buildings spatially configuration for circular city shape

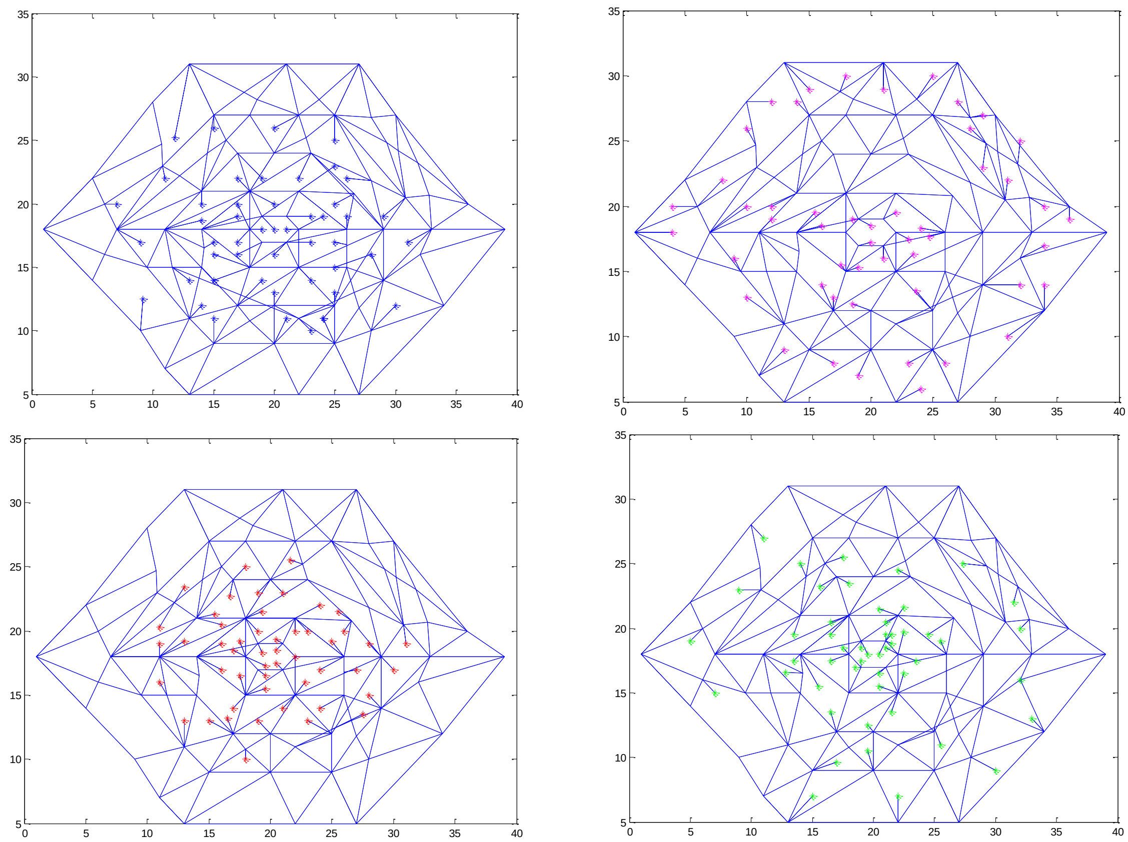


Figure 4 - Four different buildings spatially configuration for hexagonal city shape

Four different urban configurations are modeled according to the case study 1. In Figures a set of discrete links is observed, which represent street patterns. Colored starred nodes represent instead residential building nodes, which are connected to streets by fictitious links. These represent the access point from the main streets to the residential buildings.
The case study 1 considers always the same street patterns, while buildings' location is always different within the four studied topologies. Residential buildings' location is differently modeled for each city, considering for scattered locations, more peripheral locations and more central locations within the urban context.

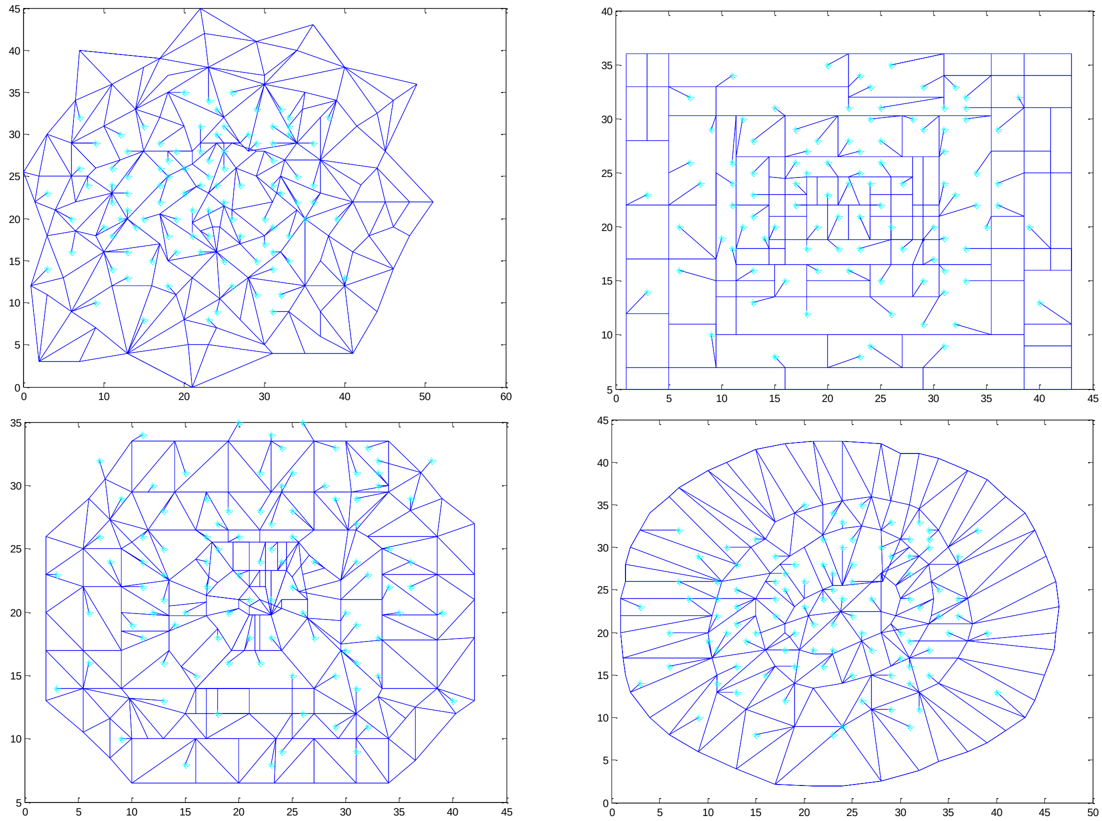


Figure 5 - Four different street patterns configurations with 200 buildings with fixed location

Just four different cities are modeled in the case study 2, one for each urban shape. Here segments shown in Figures, which define the geometric urban shape, represent streets as for the case study 1. Colored starred nodes are the building nodes, whose locations remain always the same for the four shapes, while street patterns change according to the adopted geometry. Links connecting buildings to streets are the same as in case study 1.

2.2 Efficiency assessment

In this study cities are modelled as spatial networks, which are a particular kind of complex networks and they are embedded in a space in turn associated with a metric.

Urban environment is represented through the modeling of a planar graph, usually embedded in a two-dimensional Euclidean space, whose typical metric is the Euclidean distance.

Dealing with spatial networks, it is fundamental to know in which way nodes are connected, to move or send information from a node i to a node j. A sequence alternating nodes and edges is called a *walk* from i to j, and whether each node of the walk is traversed only once, it is called a *path*. A cost is then associated to each walk/path, as the sum of all involved edges.

The path from i to j having the minimal length is called the *shortest path*, having length equal to d_{ij}. One can then gather that the lower is the length of the shortest paths and the better is the communication between any pair of nodes belonging to the network.

The concept of efficiency here is understood as the capability of the urban shape to effectively ensure connection between pair of nodes, even whether a shocking event occurs, like an earthquake.

In order to measure the network efficiency as the average reachability of its nodes, the network efficiency as proposed by Latora and Marchiori (2001) [10] is used. Hence such reachability can be measured even when the network is not connected, as typically happens in the aftermath of a disaster, when road networks get partially or totally disrupted.

The efficiency between pair of nodes is evaluated as the inverse of the length of the shortest paths connecting them, $e_{ij}=1/d_{ij}$, and it is minimal when $d_{ij}=\infty$, that is when i and j are disconnected.

Usually the efficiency between two nodes is then normalized as: $e_{ij}= d_{ij}^{eucl}/d_{ij}$, where d_{ij}^{eucl} is the Euclidean distance. The global efficiency is then assessed as the normalized pairwise efficiency, averaged on all possible pairs of nodes:

$$E = \frac{1}{N(N-1)} \cdot \sum_{\substack{i,j \in N \\ i \neq j}} \frac{d_{ij}^{eucl}}{d_{ij}} \qquad (1)$$

The global efficiency is normalized in [0,1]. This is due to the distance between node i and node j, d_{ij}, being larger than the Euclidean distance between i and j. Such a measurement of the global efficiency allows to consistently compare two distinct graphs, even whether they have a different number of nodes and links.

Actually such an equation does not allow to evaluate efficiency of the residential HSPN, since it does not account for people living in each building. Hence a further equation is defined to calculate the citizen-citizen efficiency, as outlined in Cavallaro et al. (2013) [1], as follows:

$$\begin{aligned} Ecc &= \frac{1}{H_{tot}(H_{tot}-1)} \sum_{i \in \mathrm{N}_b} H_i \cdot \left((H_i - 1) + \sum_{j \in N_b, j \neq i} H_j \frac{d_{ij}^{eucl}}{d_{ij}} \right) \\ &= \frac{1}{H_{tot}(H_{tot}-1)} \sum_{i \in \mathrm{N}_b} H_i \cdot \left((h_i - 1) + \sum_{j \in (\mathrm{N}_b \setminus \mathrm{I})} H_j \frac{d_{ij}^{eucl}}{d_{ij}} \right) \end{aligned} \qquad (2)$$

Where i, j are the indexes of building nodes, H_{tot} is the number of citizens living in the studied city, H_i is the total number of citizens living in building i, N_b is the set of building nodes, d_{ij} is the length of the shortest path connecting node i and node j and h_i is the number of citizens living in buildings, which belong to the set I, of buildings having zero distance from to building i. The result is a measure of connectivity between inhabitants inside buildings, which is obtained by summing over all couples of citizens and imposing $d_{ij}^{eucl}/d_{ij} = 1$ for inhabitants living at distance zero. This last is obviously the case in which the efficiency is maximised in communication between couples of citizens.

3 A NOVEL SYSTEMIC DAMAGE ASSESSMENT

3.1 Probability-based earthquake simulation

Earthquake scenarios are simulated for 0.25g and 0.30g PGA, which describes medium intensity seismic phenomena. Resulting building damages are simulated through the implementation of literature fragility curves, as the probability of exceedance of the "onset of damage" of each building belonging to the set of the residential ones. Hence only the exceedance of a very heavy limit state is accounted for, that is buildings are not available for occupation and use any more. Two kind of damages for the urban centre can be considered through the implementation of the vulnerability functions.

First of all, the probability of being damaged or becoming unfit for use when hit by an earthquake of a certain intensity for each building. It is represented by the fragility function, a probability law which is described by a log-normal distribution function, as follows:

$$P_b(PGA;\mu,\sigma) = \Phi\left(-\frac{\ln PGA - \mu}{\sigma}\right) \quad (3)$$

Simulations are performed considering (μ, σ)=(-0.91,0.29) for reinforced concrete buildings fragility curve from Ahmad et al. (2011) [9], which refer to the “moderate” damage state as shown in Table 1.

N° of Limit States	Limit State	Median, μ	Standard Deviation, σ
3	Slight	-1.07	0.22
	Moderate	-0.91	0.29
	Extensive	-0.71	0.27

Table 1: statistics of the fragility curve by Ahmad et al. [9]

Such a choice follows from the need of not being too conservative but also to avoid to overestimate the vulnerability of the built environment, that is clear from fitted curves, shown in Figure 6.

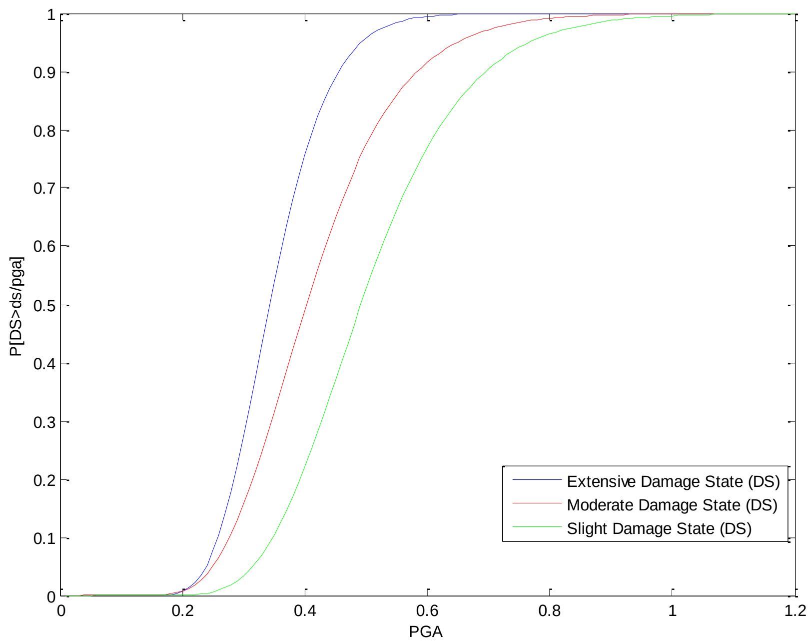


Figure 6 – Fragility curves according to Ahmad et al. for non-ductile reinforced concrete buildings

Then the probability that a damaged building limits or interrupts the transit along a street, that is adjacent to it. In fact, it is well-known that whenever an earthquake occurs, buildings located along a street could suffer damages making it inaccessible, due to the debris fallen. Moreover accessibility to a street, which is adjacent to buildings, could however be limited for safety purposes, from civil protection and other local authorities managing the emergency.

Due to this last dynamics, the street patterns probability of interruption is defined:

$$P_r(h,l) = \begin{cases} 1 & if \quad h \geq l \\ \dfrac{h}{l} & otherwise \end{cases} \tag{4}$$

Stream of uniform pseudorandom numbers is generated and values from the standard uniform distribution are selected on the open interval (0,1) and compared to the value from the fragility function, related to the PGA value attained by the simulated event. Being such value larger or smaller than those obtained from the stream simulation, decide respectively whether the building will not obstruct the adjacent street or will make it inaccessible.

This has got a further effect on the behaviour of the HSPN itself: due to the street being eventually become inaccessible, the link which represents it, will not be useful for network connectivity purposes. Hence, being the link inactive, it is removed from the network, so as the building which was adjacent to it, and caused the street usage restrictions.

Moreover damages on buildings result, for each simulated earthquake and damaged city configuration, in a certain number of citizens to be reallocated. In fact, as already explained, the number of citizens living in each city is accounted assuming a certain floor area for each storey, depending on the storeys number itself, and assuming an inhabitant each 30 square meters.

Once the city is modelled the methodology allow for the damage assessment right after a seismic event occurred, both in terms of street pattern and damaged buildings which are removed and also in terms of citizens, which remain without their homes and need to be reallocated. Ten scenario analysis are performed for each different urban geometrical configuration, drawing values from the pseudorandom number simulation, which are always different, and giving, as a consequence, different results, as shown in Figure 7 and in Figure 8:

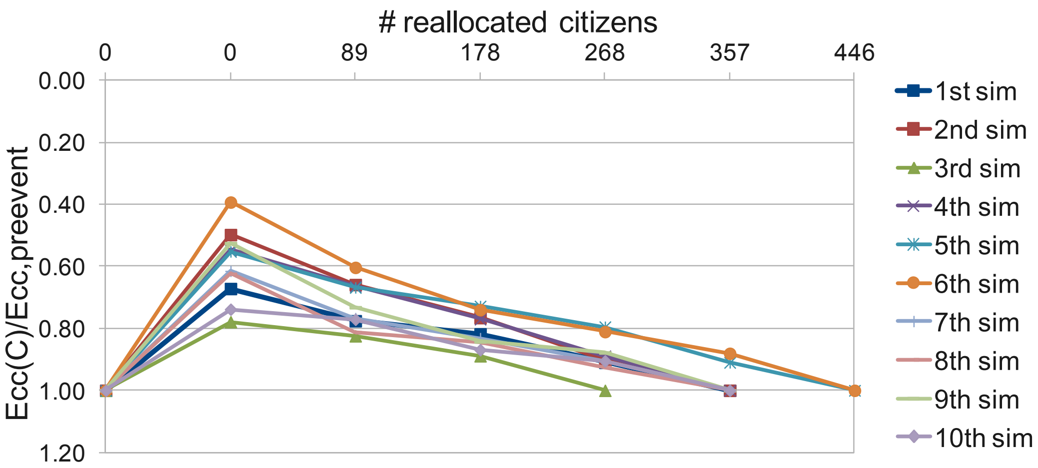


Figure 7 – Normalized efficiency against the number of reallocated citizens for the star shape HSPN, in the case of seismic scenario analysis with PGA=0.30g and 50 residential buildings with different location

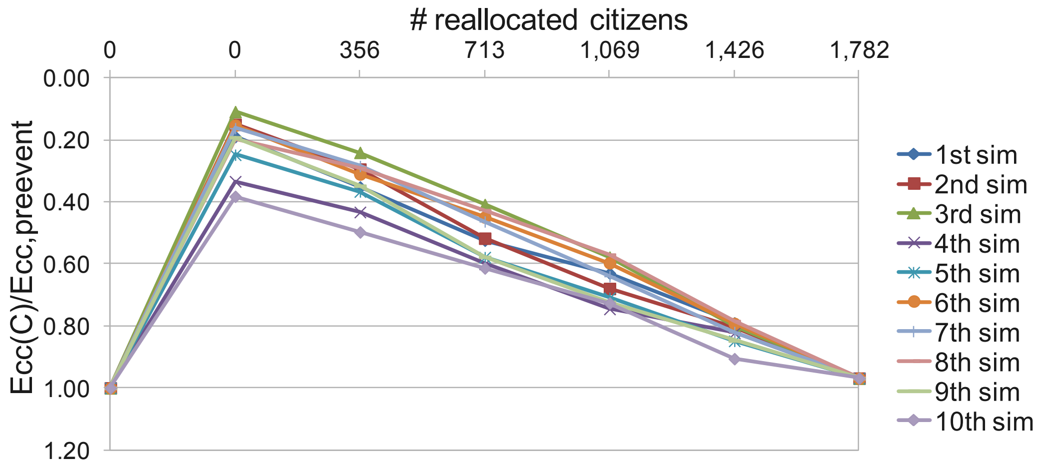


Figure 8 – Normalized efficiency against the number of reallocated citizens for the star shape HSPN, in the case of seismic scenario analysis with PGA=0.30g and 100 residential buildings with fixed location

3.2 Efficiency of damaged urban centres as a measure of the integral urban damage

Since HSPNs are modelled as graphs, the basic principle to measure their overall behaviour in a scientific manner refers to the complex network theory. Damages suffered by a city are measured starting from the single building. This is conceived as a physical structure itself, but also as an “ideal reference point”, in which citizens live and from which they are served. Urban services, such as gas and water pipelines and electric grids, and also road infrastructures are linked to such buildings. Hence, once the links between buildings and all urban services are modelled, one can simply assume that when the building goes out-of-service, even all services which are linked to it are useless. Particularly, in this work the link between the couple of nodes representing buildings are modelled based on the street patterns of the studied city. This assumption is easily justified by the fact that in nearly every urban centre urban services infrastructures (pipelines for instance), are located on the streets.

The fragility curve here implemented gives a probability-based measure of the capacity of buildings within an urban centre to withstand a seismic event. Hence, it allows to quantify the vulnerability of the built environment.

Given the assumption made, it also allows to identify which urban areas become useless whenever an earthquake occurs.

Structural measures performed through the fragility function on each single building are then extended to streets and to all urban services which are linked to it. Hence, the engineering assessment is understood as a scattered measure of each urban area usability.

On the other hand, all urban areas are mutually interrelated by further streets and services distribution plants. The evaluation of the quality of such links, the connectivity and the efficiency level leads to the knowledge of the overall behaviour of the investigated urban system. An information which is obtained through the implementation of complex networks measure techniques. Particularly, global efficiency measurement are performed according to Latora and Marchiori (2001) [10].

Finally the novelty in the assessment of the state of service of the urban environment after the occurrence of a catastrophic event is underlined, as the chance to merge civil engineering and complex networks methodologies. Such an approach, allow to perform a measurement of the after-event level of performance of the city which is a systemic and integral one. Further-more, the performed measures follow the modern multi-scale approach, from the lower to the higher degree of network complexity.

Given the residential HSPN efficiency, as evaluated in Cavallaro et al. (2013), the systemic damage measure can be simply evaluated as:

$$D = E_{cc}^{pre-event} - E_{cc}^{post-event} \qquad (5)$$

Whereas the ratio between this two quantities is also defined as the *recovery function*, as well as the normalized efficiency corresponding to the first time step soon after the earthquake has occurred:

$$\Upsilon(0) = \frac{E_{cc}^{post-event}}{E_{cc}^{pre-event}} \qquad (6)$$

Values for all investigated urban shapes for such a ratio, are shown in Table 2.

City Shape	Mean Pre-event Efficiency [$E_{cc}^{pre-event}$]	Mean Post-event Efficiency [$E_{cc}^{post-event}$]	Y(0)	D
Case 1 - Different city shape with different building location				
Hexagonal	3,034	2,512	0,826	0,523
Rectangular	2,643	2,001	0,761	0,642
Star	3,103	2,584	0,833	0,519
Circular	2,977	2,281	0,765	0,696
Case 2 - Different city shape with same building location				
Octagonal	2,603	1,075	0,413	1,529
Rectangular	2,505	1,046	0,417	1,459
Star	2,693	1,077	0,400	1,616
Circular	3,127	1,029	0,329	2,098

Table 2: Pre-event and post-event efficiency values of residential HSPNs according to different modelled geometrical forms, in the case in which building location is modelled as variable and fixed

According to the normalized efficiency values, the star and hexagonal shapes exhibit the best behaviour in case 1, while in case 2 the efficiency for octagonal, rectangular and star show values, which are very similar. From case 1 to case 2 efficiency is almost halved while the number of residential buildings is doubled. This is due to the major effort in case 2 of having efficient links. Obviously a major quantity of buildings is much difficult to get connected. Moreover the lower the distance among people in the urban network, the higher the efficiency of the residential HSPN.

Such a lower efficiency in case 2 has not to be ascribed to the building vulnerability instead, since they are all reinforced concrete buildings, whose percentage in terms of number of storeys is keeping invariant when passing from case 1 to case 2.

4 LINKING URBAN DAMAGE AND RESILIENCE ASSESSMENT

The systemic measure of damages suffered by the urban environment when a seismic event occurs are also understood according to the classical approach to urban resilience.

The recovery function, Y, is the measure of the performance of the system at a certain instant in time, t. Hence, if it is evaluated for each step of the recovery strategy implemented after the shock, the capability of the city to bounce back to its previous performance level can be assessed as the integral of such quantity in time.

Resilience is, in fact, defined as the area under the recovery curve, divided by the time passed by from the start of the recovery process, t_b, to its completion, t_c, as follows:

$$R = \frac{\int_{tb}^{tc} Y(t)dt}{(t_c - t_b)} \quad (7)$$

According to the implemented HSPN model and to the definition of the recovery function previously given:

$$Y(t) = \frac{E_{cc}(t)}{E_{cc}^{pre-event}} \quad (8)$$

In fact, while Y(0) is the value of the recovery function soon after the occurrence of the earthquake, Y(t) is the same function evaluated for each step of the recovery strategy.

Such formulation requires a good knowledge of the state of service of the city for each step of time, during reconstruction. But it depends on several factors (available monetary budget, promptness of reconstruction, first aid time, etc.) and it is not easy to know in detail, so any dependence on time is removed and the recovery function is calculated depending on the number of reallocated citizens, C, for each step of the recovery strategy:

$$Y(C) = \frac{E_{cc}(C)}{E_{cc}^{pre-event}} \quad (9)$$

Also the dependence on total damage is removed by defining:

$$y(C) = \frac{Y(C) - Y(0)}{1 - Y(0)} \quad (10)$$

Where Y(0) is zero in the aftermath of the seismic event, that is when no citizen has been yet reallocated. And disaster resilience is then calculated through the following:

$$R = \frac{\int_{0}^{C\max} y(C)dC}{C\max} = \frac{\sum_{c=0}^{C\max} y(C)}{C\max} \quad (11)$$

Where Cmax is the total number of citizens to reallocate after the earthquake and the integral is simplified with a summation, being the strategy implemented in a discrete number of steps.

In this study, a recovery strategy is hypothesized according to which first cheaper buildings are restored after the earthquake. Hence, efficiency is evaluated, for each urban shape, for each step of the recovery strategy and then it is integrated by the number of reallocated citizens to compute resilience. Mean values from simulation are fitted against the number of reallocated citizens for each urban geometry in the case of an earthquake of PGA=0.25g and in the case of an earthquake of PGA=0.30g for both the case of study 1 and 2 (Figures 9 – 12).

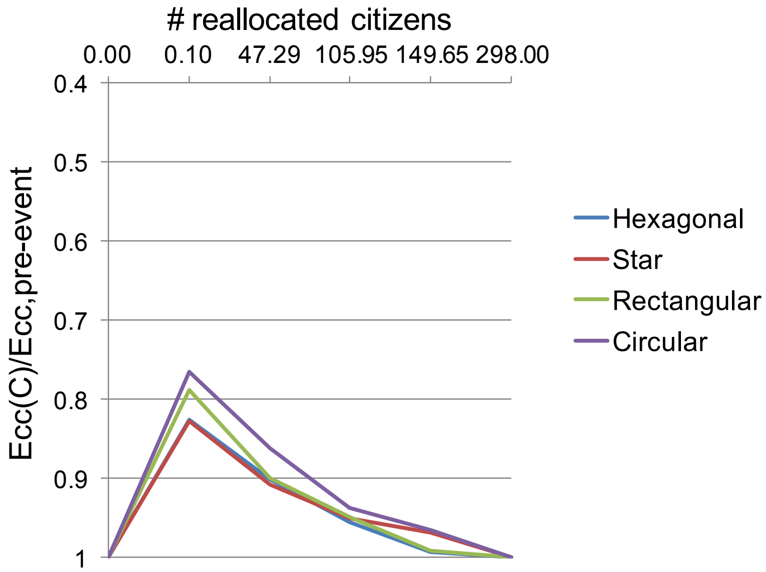


Figure 9 – Normalized efficiency against number of reallocated citizens in the case of different buildings location (Case 1) and PGA=0.25g

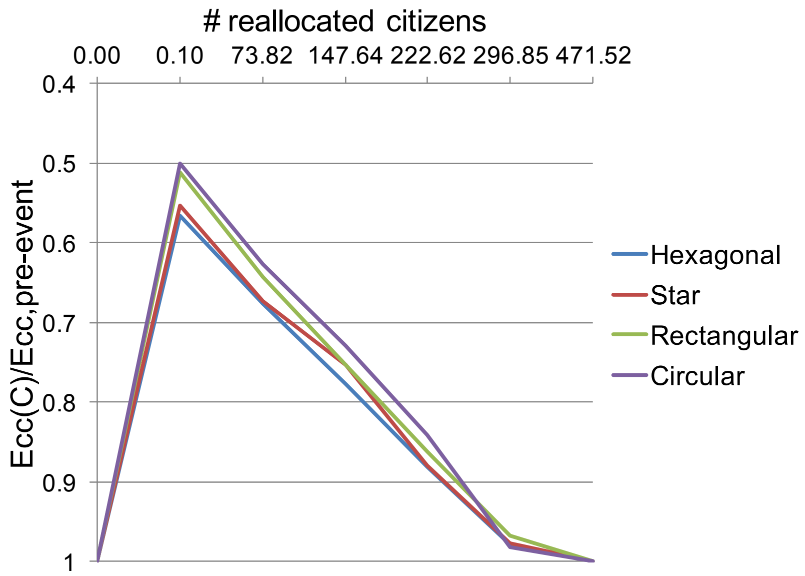


Figure 10 - Normalized efficiency against number of reallocated citizens in the case of different buildings location (Case 1) and PGA=0.30g

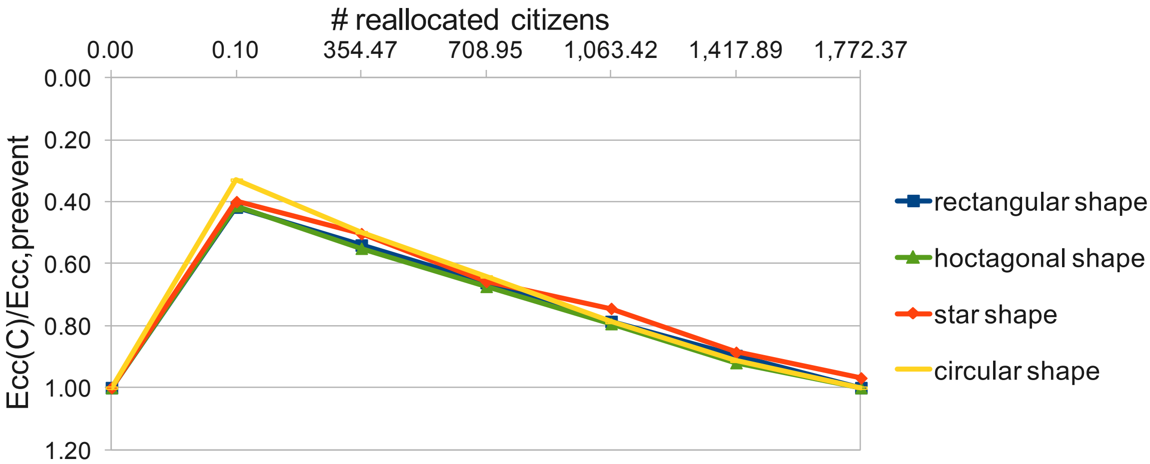


Figure 11 – Normalized efficiency against number of reallocated citizens in the case of fixed buildings locations (Case 2) and PGA=0.25g

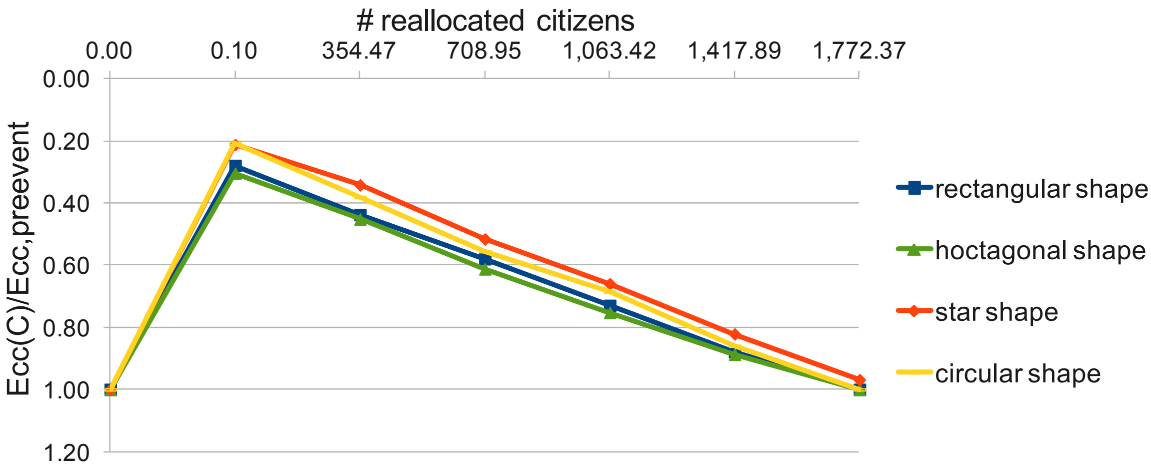


Figure 12 – Normalized efficiency against number of reallocated citizens in the case of fixed buildings locations (Case 2) and PGA=0.30g

Experimental results show a clear major downfall of the efficiency curve in the case of an earthquake occurrence whose PGA is 0.30g. Obviously the more intense is the earthquake the many more buildings are damaged, and many more citizens are deallocated too. A major slope is outlined in case 1 between star and hexagonal shapes, which are clearly more efficient, rectangular and circular shapes. Conversely, in case 2 the behavior seems to be much similar even when geometric shape changes. There are slight differences in the case of an earthquake of PGA=0.25g in which the circular shape reveals to be the less efficient one, and such a behavior is confirmed when PGA=0.30g , together with the star shape.

All things considered no major differences are revealed when comparing results in terms of resilience from case study 1 and case study 2. Hence,

Considerations are validated when performing the resilience assessment for each geometry in the two case studies, which is averaged on the ten scenario simulations performed for each of them, as shown in Table 3.

RESILIENCE		
Case 1 - Different spatial buildings configuration and same links	PGA=0.25	PGA=0.30
RECTANGULAR	0,0168	0,0092
HEXAGONAL	0,0146	0,0086
STAR	0,0200	0,0085
CIRCULAR	0,0142	0,0080
Case 2 - Fixed spatial buildings configuration and different links	PGA=0.25	PGA=0.30
RECTANGULAR	0,0031	0,0024
OCTAGONAL	0,0031	0,0024
STAR	0,0033	0,0021
CIRCULAR	0,0032	0,0022

Table 3 – Mean seismic resilience assessed for each urban geometry in the case of an earthquake with magnitudes, PGA=0.25g and PGA=0.30g

5 CONCLUSIONS

The present study focus on the evaluation of the efficiency of cities when subjected to seismic events according to their topological structure. A methodology merging civil engineering and complex networks metrics is implemented in order to assess the global state of damage and the urban resilience. The equation used for the quantification of resilience allows to appreciate the efficiency in the recovery process of a city after a disaster has occurred. Efficiency is then evaluated closely after the earthquake and has to be compared with as many strategies for reconstruction.

The paper proposes a novel approach which take also into account people living in a city, through the modeling of urban centres as hybrid social-physical networks (HSPNs). Urban street patterns and infrastructures are modelled as undirected graphs, and also citizens are considered as the sensors of urban efficiency and connectivity.

Earthquake scenarios are simulated and a recovery strategy is hypothesized. A probability-based approach is used to evaluate buildings' vulnerability and urban efficiency measure soon after the earthquake occurrence are used as a systemic measure of the overall damage suffered by each investigated urban centre.

Resilience is then evaluated for each urban shape and each earthquake scenario.

Results show some differences in resilience levels, with the star shape in every case the most efficient and the circular one the worst.

Not significant differences have been instead recorded for the different city geometries, while considering the different number of links between fixed building distributions. Even if higher slope in the efficiency level is observed for urban shapes investigated in the case study 2 with respect to those in the case study 1. This can be attributes to the higher number of residential buildings being modelled within the second case study (they are doubled), which makes cities more exposed. Hence, for the same simulated seismic intensity the global response in terms of both efficiency and resilience is quite similar in the two case studies. But if the urban efficiency is observed within a time-discrete analysis, it is clear that major problems and inconveniences are expected in the case study 2. That is the case in which many more buildings are located within the studied urban area.

Further analysis are needed, with the purpose to model urban networks with many more buildings and real cases to be compared with.

Moreover further developments are needed to compare attained urban resilience when different recovery strategies are implemented.

The proposed methodology can be an effective mean, to used as a support for disaster management. Best practises can be recognised for each investigated topology, by implementing scenario analysis in which different recovery strategies are adopted and by comparing the evaluated resilience and efficiency for each of them.

The proposed methodology has a dual application field, being potentially used as an effective engineering mean to quantify a unique indicator as a vectorial measure of city damages. On the other hand, the quantification of resilience being reiterated for each city, different magnitudes of simulated disaster and different hypothesized recovery strategies, is a very powerful mean to be used as a support for urban planning and disaster management.

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